3.1 Gulf of Maine cod

Catch and Survey Indices

Atlantic cod (*Gadus morhua*) in the Gulf of Maine region have been commercially exploited since the 17th century, and reliable landings statistics are available since 1893. Historically, the Gulf of Maine fishery can be separated into four periods: (1) an early era from 1893-1915 in which record-high landings (> 17,000 mt) in 1895 and 1906 were followed by about 10 years of sharply-reduced catches; (2) a later period from 1916-1940 in which annual landings were relatively stable, fluctuating between 5,000 and 11,500 mt, and averaging 8,300 mt per year; (3) a period from 1941-1963 when landings sharply increased (1945: 14,500 mt) and then rapidly decreased, reaching a record-low of 2,600 mt in 1957; and (4) the most recent period from 1964 onward during which Gulf of Maine landings have generally increased but have declined steadily since the early 1990s. Commercial landings doubled between 1964 and 1968, doubled again between 1968 and 1977, and averaged 12,200 mt per year during 1976-1985 (Figure 3.1.1). Gulf of Maine cod landings subsequently increased, reaching 17,800 mt in 1991, the highest level since the early 1900s.

Commercial landings declined sharply in 1992, and have since decreased steadily to 1,636 mt in 1999 before increasing to 3,730 mt in 2000. The sharp decline in landings between 1998 and 1999 and the subsequent increase in 2000 likely reflects the imposition of very low trip limits during 1999 and the subsequent relaxation of these limits in early 2000. The extent of discarding increased sharply in 1999 and remained relatively high in 2000. Landings of Gulf of Maine cod from the recreational sector have also been significant, averaging about 20% of the total (commercial and recreational) landings since 1982.

Fishery-independent spring and autumn bottom trawl surveys conducted by the NEFSC have documented a steady decline in total stock biomass since the 1960s; the largest decreases occurred during the 1980s (Figure 3.1.1). Although the most recent indices suggest a slight increase, overall, the Gulf of Maine cod stock biomass remains low relative to the 1960s and 1970s.

Stock Assessment

The most recent assessment of the Gulf of Maine cod stock was completed in 2001 (Mayo *et al.* 2002a), and the results were reviewed at the 33rd Northeast Regional Stock Assessment Workshop in June, 2001 (NEFSC 2001c). At that time fully recruited fishing mortality in 2000 was estimated to be 0.73. Spawning stock biomass had increased slightly from 9,900 mt in 1998 to 13,100 mt in 2000, still well below the maximum of 24,200 mt observed during the 1982-2000 VPA period. Except for the 1998 year class, recruitment had been relatively poor since the appearance of the 1992 year class. Plots of spawning stock biomass (SSB) and recruitment estimates obtained from the 2001 assessment are provided in Figure 3.1.2. Over the range of spawning stock observed during the VPA period (1982-2000), there appears to be no appreciable trend in recruitment with respect to SSB.

Fishing mortality (fully recruited) and biomass reference points were estimated from a yield and spawning biomass per recruit analysis combined with a stock-recruitment analysis employing a parametric Beverton-Holt model. The following reference points were estimated: $F_{0.1}$ = 0.15, F_{msy} = 0.23, F_{max} = 0.27, B_{msy} = 90,300 mt, and SSB_{msy} = 78,000 mt.

Yield and SSB per Recruit Analysis

The yield and spawning stock biomass analysis conducted during the course of the 2001 assessment was revised slightly during the present analysis to achieve consistency with the likely age distribution of fish within the plus group by adjusting the age 11+ mean weight at age to account for the F likely to rebuild spawning biomass. Partial recruitment and maturation at age were the same as those employed in the 2001 assessment. Estimates of $F_{0.1}$ and F_{max} presented in Table 3.1.2 are virtually identical to those given in the 2001 assessment. The yield and spawning stock biomass per recruit estimated over a range of fishing mortality rates were employed in the estimation of MSY-based reference points as described in the following section.

MSY-based Reference Point Estimation

<u>Empirical Nonparametric Approach</u>

The stock-recruitment data derived from the 2001 VPA do not suggest any appreciable trend in recruitment with respect to spawning stock biomass, the average recruitment from the entire series is used to represent the expected recruitment at Bmsy (Figure 3.1.2). If the estimate of F40% is taken as a proxy for Fmsy, the fishing mortality threshold is 0.166. This fishing mortality rate produces 11.412 kg of spawning stock biomass per recruit and 1.7913 kg of yield per recruit. The resulting mean of 7.67 million fish results in an SSB_{msy} estimate of 87,580 mt when multiplied by the SSB per recruit, and an MSY estimate of 13,739 mt when multiplied by the yield per recruit.

Although this estimate of SSB_{msy} is well above the range of SSB observed during the VPA period, a series of hindcast spawning biomass and recruitment estimates based on autumn NEFSC surveys (Figure 3.1.3) suggests the existence of SSB levels during the1960s which were well above the maximum estimate from the VPA.

<u>Parametric Model Approach</u>

Maximum likelihood fits of the 10 parametric stock-recruitment models to the Gulf of Maine cod data from 1982-2000 are listed below (Table 3.1.1). The model acronyms are:
BH = Beverton-Holt, ABH = Beverton-Holt with autoregressive errors, PBH = Beverton-Holt with steepness prior, PABH = Beverton-Holt with steepness prior and autoregressive errors, PRBH = Beverton-Holt with recruitment prior, PRABH = Beverton-Holt with recruitment prior and autoregressive errors, RK = Ricker, ARK = Ricker with autoregressive errors, PRK = Ricker

with slope at the origin prior, PARK = Ricker with slope at the origin prior and autoregressive errors. The six hierarchical criteria are applied to each of the models to determine the set of candidate models.

The first criterion is not satisfied by the PRK and PARK models because the estimate of F_{MSY} lies on the boundary of its feasible range. The second criterion is not satisfied by the PBH model which has a point estimate of MSY=21.300 mt. This eliminates the PBH as a candidate. The third criterion is satisfied by the remaining models. The fourth criterion is not satisfied by the RK and ARK models, where the F_{MSY} estimates of 0.60 greatly exceed the value of F_{MAX} =0.27 for Gulf of Maine cod. The fifth criterion is not satisfied by the remaining autoregressive models which have dominant frequencies greater than ½ of the length of the rather short stock-recruitment time series for Gulf of Maine cod (Figure 3.1.4). Finally, the sixth criterion is considered to be satisfied by the remaining 2 models: BH and PRBH.

Given the two candidate models (BH and PRBH), the AIC criterion assigns a slightly greater probability to the PRBH model. The odds ratio of BH being true to PRBH is roughly 1.1:1. There is limited basis for choosing between these two parametric models, although their point estimates of $S_{MSY,}$ F_{MSY}, and MSY differ. The two model differ only in the inclusion of a prior on recruitment in the PRBH model. However, given the limited range of the stock and recruitment data for Gulf of Maine cod, this may not be the most appropriate choice. As well, the steepness estimated by the BH model (0.91) was within $\pm$1 standard error of the average for the cod group while the steepness estimated by the PRBH model (0.95) was outside of $\pm$1 standard error and very close to the boundary (1.0). Therefore, the Beverton-Holt model without priors was considered to best fit the data for this stock.

The results of using the BH model as the best fit parametric model are shown below (Table 3.1.1 and Figures 3.1.5, 3.1.6 and 3.1.7). The standardized residual plot of the fit of the BH model to the stock-recruitment data shows that the standardized residuals generally lie within ± two standard deviations of zero (Figure 3.1.5), with the exception of the 1988 data point. MSY-based reference points derived from the BH model are: F_{msy} = 0.225 and SSB_{msy} = 82,830 mt.

In the equilibrium yield plot (Figure 3.1.6), the yield surface is relatively flat in the neighborhood of the point estimate of F_{MSY} = 0.225. The point estimates of SSB_{MSY} (82.8 kt) and MSY (16.6 kt) appear consistent with the nonparametric proxy estimate of SSB_{MSY} and previous estimates of F_{MSY} and SSB_{msy} from SAW 33. The stock-recruitment plot (Figure 3.1.7) shows that recruitment values near SSB_{MSY} are roughly 9 million fish which is slightly larger than the long-term average of the observed recruitment series but is consistent with the 75th percentile of the observed recruitment series (9.5 million fish).

Parameter uncertainty plots show histograms of 5000 MCMC sample estimates of MSY, S_{MSY}, and F_{MSY} drawn from the posterior distribution of the MLE based on an uninformative prior. Both MSY and S_{MSY} had distributions with high positive skewness. For MSY, the 80 percent credibility interval was (14.1, 34.6) with a median of 19.3 kt (Figure 3.1.8). For S_{MSY}, the 80 percent credibility interval was (66.3, 193.6) with a median of 99.1 kt (Figure 3.1.8). For F_{MSY}, the 80 percent credibility interval was (0.195, 0.240) with a median of 0.215 (Figure 3.1.8).

Overall, the point estimates of MSY and S_{MSY} were lower than the medians of the MCMC samples.

Reference Point Advice

Reference points derived from the Beverton-Holt model are: F_{msy} = 0.225, MSY = 16,600 mt and SSB_{msy} = 82,830 mt. The estimate of MSY represents total catch, including commercial and recreational landings, and commercial discards.

The revised SSBmsy estimate for Gulf of Maine cod (82,800 mt) is slightly higher than the value estimated during SAW 33 (78,000 mt) (NEFSC 2001c). The change is a result of a slight increase in the stock mean weights at age applied to the yield per recruit calculations in the age structured production model resulting in higher biomass per recruit ratios. The increase in the mean weights at age is due a change in the time period used in the averaging from long term (1982-1998) in the SAW 33 to a more recent period (1996-1998) in the present analysis.

Projections

Stochastic age-based projections (Brodziak and Rago MS 2002) were performed over a 10-year time horizon beginning in 2001 to evaluate relative trajectories of stock biomass and catch under various fishing mortality scenarios. Recruitment was derived from the Beverton-Holt spawning stock-recruitment relationship employed in the age structured production model. Stock and catch mean weights at age, the maturity at age schedule, and the partial recruitment at age vector are the same as those employed in the yield and SSB per recruit analyses presented above. The 2001 survivors derived from 600 bootstrap iterations of the final VPA formulation were employed as the initial population vector. The projection was performed at two fishing mortality rates: F_{msy} (0.225) and F calculated to rebuild spawning biomass to SSB_{msy} by 2009. Fully recruited fishing mortality in 2001 was derived from iterative calculations based on the estimated total 2001 catch (7,994 mt), including commercial landings and discards and recreational landings. Fishing mortality in 2002 was fixed at the Amendment 7 target (F_{max} = 0.26), the present management target.

The medium-term projections (Figures 3.1.9, 3.1.10, and 3.1.11) suggest that fishing at F_{msy} (0.225) between 2003 and 2009 will result in only a 22% probability of rebuilding spawning biomass to SSB_{msy} (82, 830 mt) by 2009 (Figure 3.1.9). To achieve a 50% probability of rebuilding spawning biomass to SSB_{msy} by 2009, F must be reduced to 0.165 during 2003-2009 (Figures 3.1.9 and 3.1.10). The total annual catch, including commercial landings and discard and recreational landings, is expected to increase from 3,850 mt in 2003 to 11,530 mt in 2009 (Figure 3.1.11).

Table 3.1.1. Stock-recruitment model comparisons for Gulf of Maine cod - age 11+ formulation.

Gulf of Maine Cod 11-Age Class Model Comparison										
SMAX =	77500									
	Prior	Prior	Prior	Prior	Prior	Prior	Prior	Prior	Prior	Prior
	0.5000	0	0	0	0.5000	0	0	0	0	0
	BH	**ABH**	**PBH**	**PABH**	**PRBH**	**PRABH**	RK	ARK	PRK	PARK
Posterior Probability	**0.52**	0.00	**0.00**	0.00	**0.48**	0.00	0.00	0.00	0.00	0.00
Odds Ratio for Most Likely Model	1.00				1.06					
Normalized Likelihood	0.52	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.00
Model AIC Ratio	1.06449				1					
	BH	**ABH**	**PBH**	**PABH**	**PRBH**	**PRABH**	**RK**	**ARK**	**PRK**	**PARK**
Number_of_data_points	18	18	18	18	18	18	18	18	18	18
Number_of_parameters	3	4	3	4	3	4	3	4	3	4
Negative_loglikelihood	172.151	171.265	170.666	169.886	180.249	179.296	172.104	171.195	186.623	177.639
Bias-corrected_AIC	352.016	353.607	352.171	353.933	352.141	353.609	351.922	353.467	373.269	363.252
Diagnostic Comments	**Most Likely Model**	Power spectrum dominant frequency exceeds 1/2 time series length	MSY outside range of observed landings	Power spectrum dominant frequency exceeds 1/2 time series length		Power spectrum dominant frequency exceeds 1/2 time series length	FMSY substantially exceeds FMAX	FMSY substantially exceeds FMAX	FMSY at boundary of feasible range	FMSY at boundary of feasible range
Parameter Point Estimates										
***********************										
MSY	16636.6	14090.3	21293.5	20252.6	13931.9	13787.8	10912.8	10829.7	18113.3	13385.9
FMSY	0.225	0.24	0.21	0.21	0.24	0.245	0.595	0.595	2	2
SMSY	82829.7	66237.8	112815	107300	65493.6	63648.3	25607.3	25412.1	23494.3	17362.5
alpha	9854.36	7998.51	13240.5	12522	7910.29	7780.58	0.0107473	0.00556144	0.904107	1.03259
expected_alpha	11313.5	9176.81	15219.2	14371.3	9090.31	8928.95	0.0123317	0.00637066	1.23523	1.14695
beta	7516.1	3275.83	15537.3	14087.2	3253.36	2809.65	-5.34E-05	-5.36E-05	-6.26E-05	-9.21E-05
RMAX	8983.15	7674.13	11029.3	10596	7591.6	7508.37	1252.84	1226.64	1494.91	172.625
expected_RMAX	10313.3	8804.65	12677.6	12160.8	8724.08	8616.56	1437.54	1405.12	2042.4	191.743
Prior_mean			0.84	0.84	7674	7674			1.37	1.37
Prior_se			0.08	0.08	1226	1226			0.15	0.15
Z_Myers	0.91	0.95	0.86	0.87	0.95	0.95				
sigma	0.52552	0.524261	0.528	0.525	0.527	0.525	0.524	0.521	0.790	0.458
phi		0.31		0.28		0.31		0.30		0.38
sigmaw		0.499		0.50		0.50		0.50		0.42
last log-residual R		-0.088		0.024		-0.094		-0.086		-0.684
expected lognormal error term	1.148	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.37	1.11

Table 3.1.2. Yield and biomass per recruit for Gulf of Maine cod.

The NEFC Yield and Stock Size per Recruit Program - PDBYPRC
PC Ver.2.0 [Method of Thompson and Bell (1934)] 9-Aug-2001

Run Date: 21- 2-2002; Time: 10:44:58.63
GULF OF MAINE COD (5Y) - 2001 UPDATED AVE WTS, FPAT AND MAT VECTORS

Proportion of F before spawning: .1667
Proportion of M before spawning: .1667
Natural Mortality is Constant at: .200
Initial age is: 1; Last age is: 11
Last age is a PLUS group;
Original age-specific PRs, Mats, and Mean Wts from file:
==> yrcodgma.dat

Age-specific Input data for Yield per Recruit Analysis

Age	Fish Mort Pattern	Nat Mort Pattern	Proportion Mature	Average Weights Catch	Average Weights Stock
1	.0000	1.0000	.0400	.468	.264
2	.0134	1.0000	.3800	1.582	.860
3	.2867	1.0000	.8900	2.064	1.811
4	.9899	1.0000	.9900	2.726	2.336
5	1.0000	1.0000	1.0000	3.982	3.314
6	1.0000	1.0000	1.0000	5.804	4.659
7	1.0000	1.0000	1.0000	9.569	7.916
8	1.0000	1.0000	1.0000	12.507	10.889
9	1.0000	1.0000	1.0000	16.015	14.253
10	1.0000	1.0000	1.0000	18.709	16.199
11+	1.0000	1.0000	1.0000	19.198	17.472

Summary of Yield per Recruit Analysis for:
GULF OF MAINE COD (5Y) - 2001 UPDATED AVE WTS, FPAT AND MAT VECTORS

Slope of the Yield/Recruit Curve at F=0.00: --> 29.4040
F level at slope=1/10 of the above slope (F0.1): -----> .151
Yield/Recruit corresponding to F0.1: -----> 1.7547
F level to produce Maximum Yield/Recruit (Fmax): -----> .258
Yield/Recruit corresponding to Fmax: -----> 1.8744
F level at 40 % of Max Spawning Potential (F40): -----> .166
SSB/Recruit corresponding to F40: --------> 11.4116

1

Listing of Yield per Recruit Results for:
GULF OF MAINE COD (5Y) - 2001 UPDATED AVE WTS, FPAT AND MAT VECTORS

	FMORT	TOTCTHN	TOTCTHW	TOTSTKN	TOTSTKW	SPNSTKN	SPNSTKW	% MSP
	.000	.00000	.00000	5.5167	30.3366	3.8396	28.5329	100.00
	.050	.11707	1.03050	4.9337	22.1467	3.2550	20.4493	71.67
	.100	.19537	1.52129	4.5446	17.0849	2.8642	15.4734	54.23
	.150	.25150	1.75096	4.2662	13.7410	2.5841	12.1992	42.75
F0.1	.151	.25271	1.75465	4.2602	13.6723	2.5781	12.1320	42.52
F40%	.166	.26582	1.79128	4.1953	12.9345	2.5127	11.4116	39.99
	.200	.29377	1.84734	4.0571	11.4231	2.3734	9.9383	34.83
	.250	.32681	1.87408	3.8941	9.7562	2.2088	8.3179	29.15
Fmax	.258	.33155	1.87438	3.8708	9.5287	2.1852	8.0972	28.38
	.300	.35338	1.86457	3.7634	8.5212	2.0765	7.1212	24.96
	.350	.37523	1.83693	3.6562	7.5835	1.9677	6.2151	21.78
	.400	.39356	1.80113	3.5666	6.8563	1.8766	5.5141	19.33
	.450	.40917	1.76268	3.4906	6.2820	1.7990	4.9615	17.39
	.500	.42264	1.72460	3.4252	5.8209	1.7321	4.5185	15.84
	.550	.43440	1.68842	3.3683	5.4454	1.6737	4.1580	14.57
	.600	.44477	1.65490	3.3184	5.1354	1.6223	3.8607	13.53
	.650	.45399	1.62429	3.2741	4.8766	1.5766	3.6124	12.66
	.700	.46225	1.59660	3.2345	4.6580	1.5356	3.4026	11.93
	.750	.46971	1.57170	3.1990	4.4715	1.4987	3.2235	11.30
	.800	.47648	1.54936	3.1668	4.3110	1.4651	3.0692	10.76
	.850	.48266	1.52937	3.1376	4.1716	1.4345	2.9350	10.29
	.900	.48833	1.51148	3.1109	4.0496	1.4065	2.8173	9.87
	.950	.49355	1.49547	3.0863	3.9420	1.3806	2.7133	9.51
	1.000	.49839	1.48112	3.0637	3.8464	1.3567	2.6207	9.18

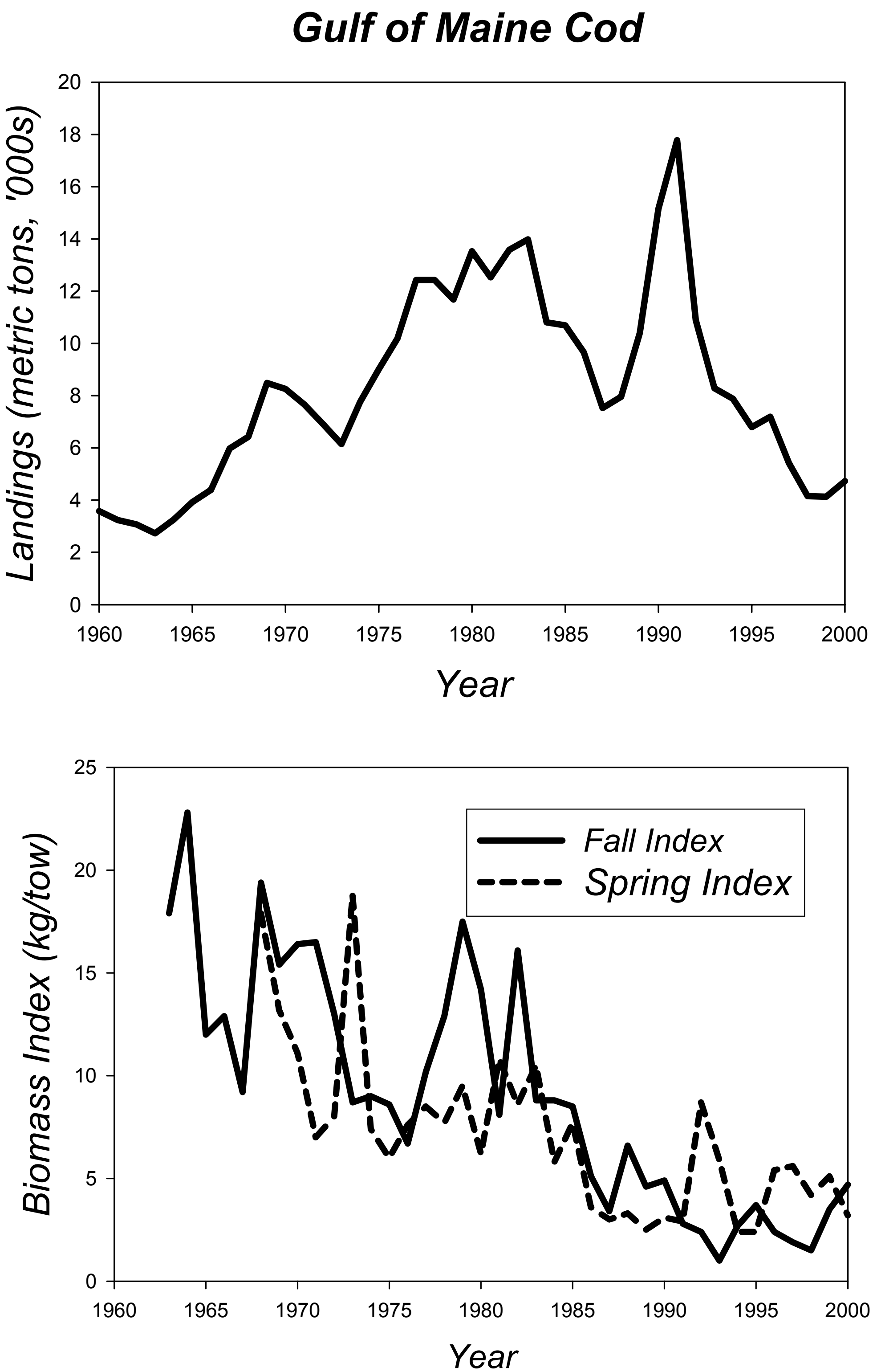
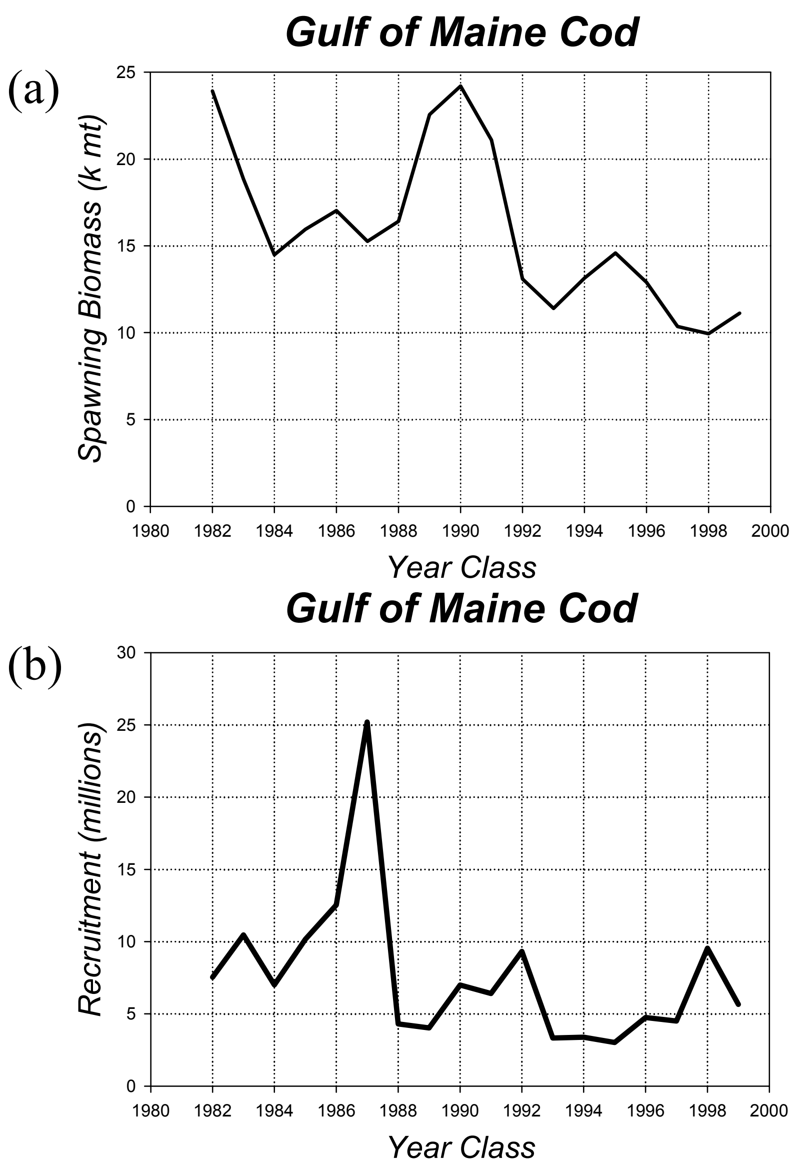
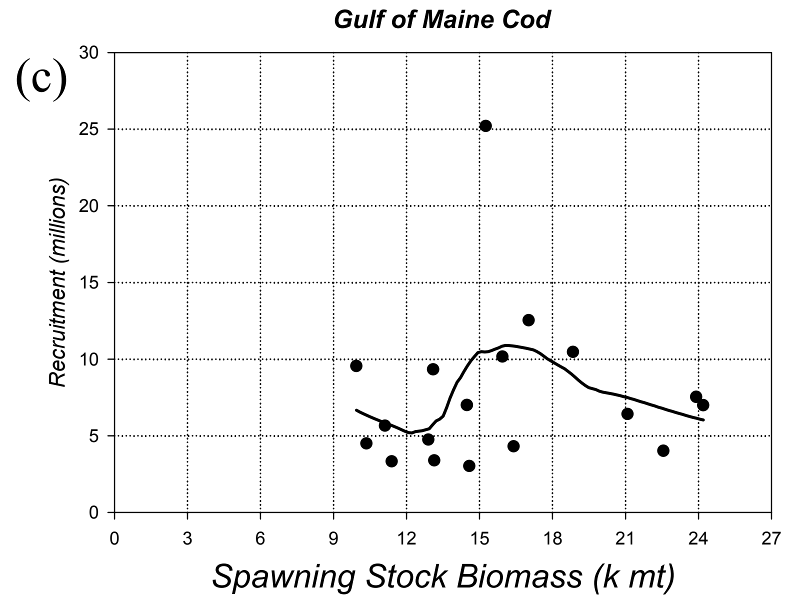


Figure 3.1.1. Landings and research vessel survey abundance indices for Gulf of Maine cod.

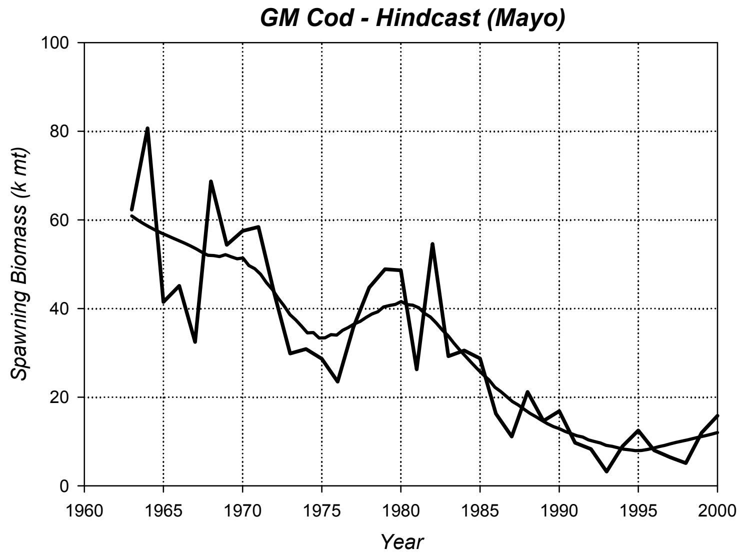




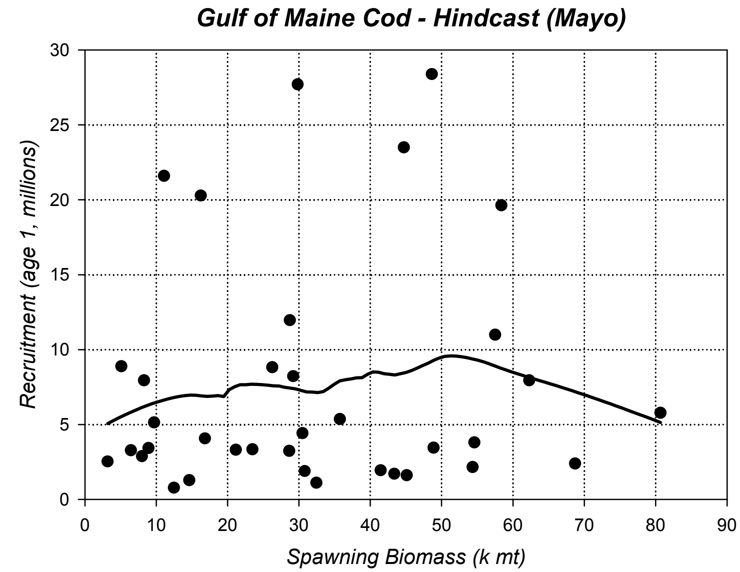
		F0.1	F40% MSP
F reference point		0.151	0.166
ssb per recruit at F		12.132	11.412
	Recruitment (millions)	SS Biomass at F0.1	SS Biomass at F40%
n	18	18	18
mean	7.67	93.10	87.58
min	3.02	36.64	34.46
max	25.20	305.70	287.55
10th %'tile	3.37	40.86	38.43
25th %'tile	4.35	52.79	49.65
50th %'tile	6.70	81.30	76.47
75th %'tile	9.49	115.18	108.34
90th %'tile	11.09	134.50	126.51
Std Dev	5.20	63.10	59.35
CV	0.68	0.68	0.68
For Top 5 values of SSB			
Mean	7.09	85.96	80.86
Median	6.99	84.83	79.79

Figure 3.1.2. Spawning stock (a), recruitment (age 1 millions, b), and scatterplot (c) for Gulf of Maine cod. Data are the calculated spawning stock biomasses for various recruitment scenarios multiplied by the expected SSB per recruit for F0.1 and F40% MSP, assuming recent patterns of growth, maturity and partial recruitment at age (Table 3.1.2). Smoother in the stock-recruitment plot is lowess with tension = 0.5.

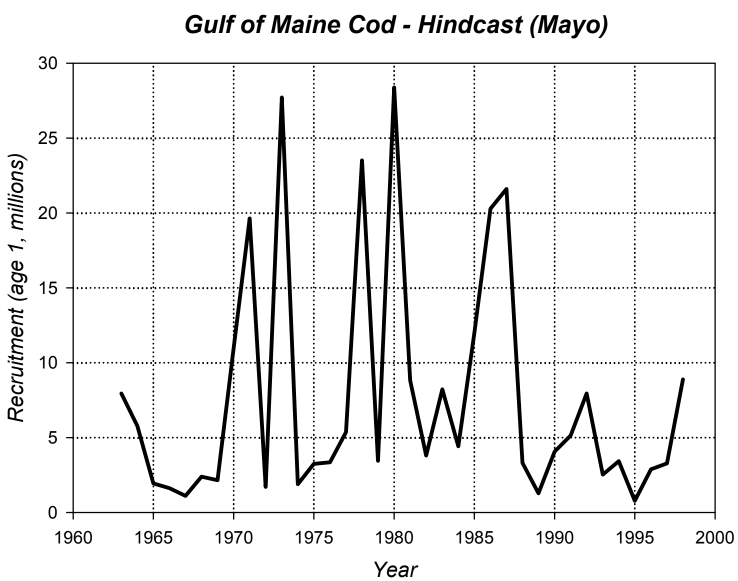
(a)



(c)



(b)



		F0.1	F40% MSP
F reference point		0.151	0.166
ssb per recruit at F		12.132	11.412
	Recruitment (millions)	SS Biomass at F0.1	SS Biomass at F40%
n	36	36	36
mean	7.63	92.62	87.12
min	0.78	9.43	8.87
max	28.38	344.34	323.91
10th %'tile	1.66	20.17	18.97
25th %'tile	2.50	30.28	28.48
50th %'tile	3.93	47.73	44.90
75th %'tile	8.84	107.26	100.90
90th %'tile	20.94	254.04	238.96
Std Dev	7.84	95.16	89.51
CV	1.03	1.03	1.03
For Top Quartile of SSB			
Mean	9.39	113.97	107.20
Median	5.78	70.14	65.98

Figure 3.1.3. Spawning stock (a), recruitment (age 1 millions, b), and scatterplot (c) for Gulf of Maine cod. Data are hindcast back to 1963 and are the calculated spawning stock biomasses for various recruitment scenarios multiplied by the expected SSB per recruit for F0.1 and F40% MSP, assuming recent patterns of growth, maturity and partial recruitment at age (Table 3.1.2). Smoother in the stock-recruitment plot is lowess with tension = 0.5, for the spawning biomass plot, the lowess smoother tension = 0.3.

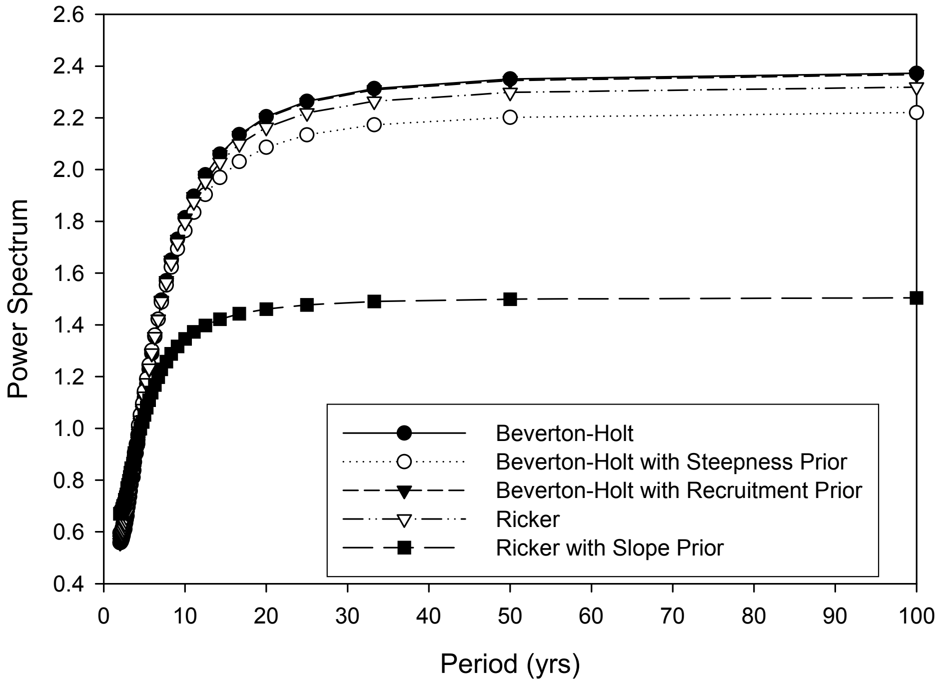


Figure 3.1.4. Gulf of Maine cod 11+ periodicity of environmental forcing for Autoregressive stock-recruitment models.

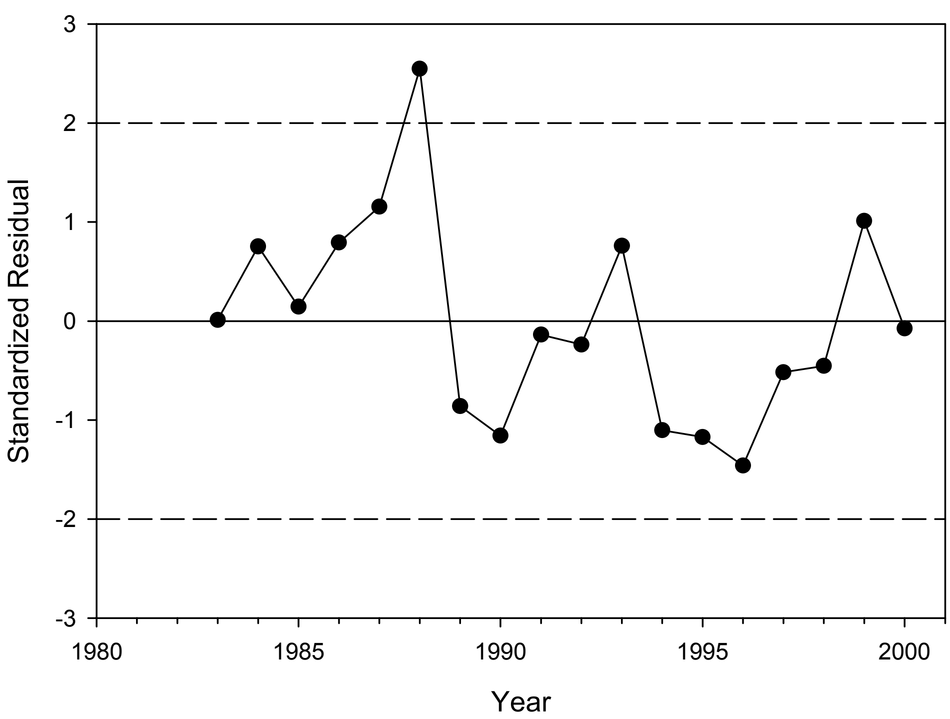


Figure 3.1.5. Gulf of Maine cod 11+ standardized residuals for the most likely stock-recruitment model

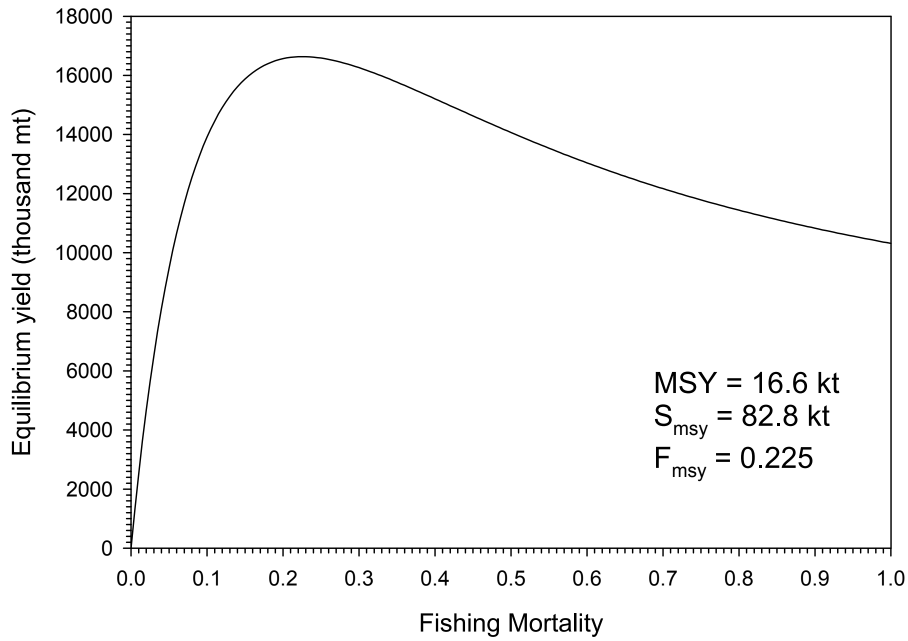


Figure 3.1.6. Gulf of Maine cod 11+ equilibrium yield vs. F for the most-likely Stock-recruitment model.

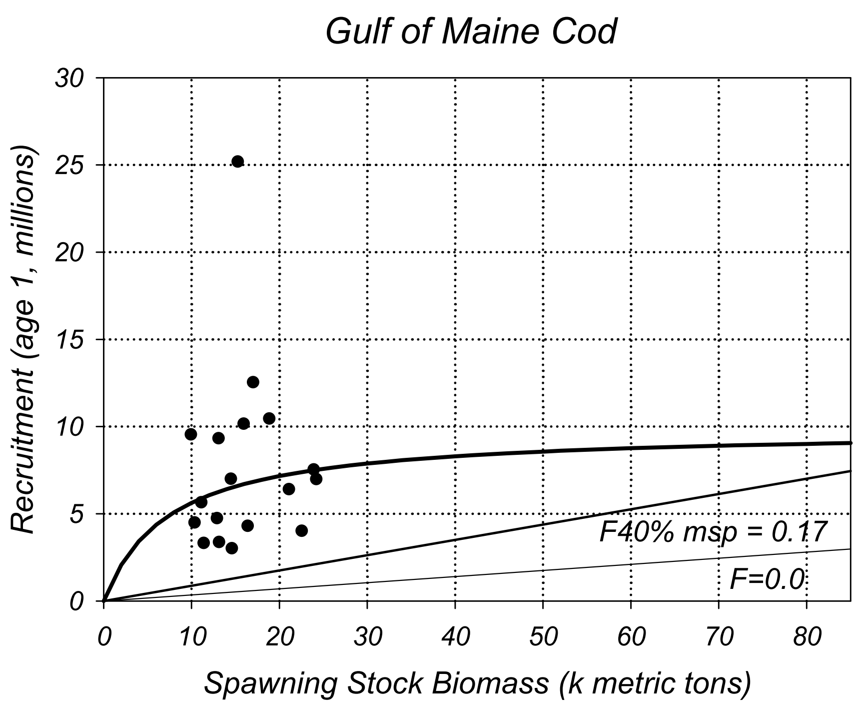


Figure 3.1.7. Stock recruitment relationship for best fit parametric model for Gulf of Maine cod. Stock-recruitment data points are overplotted, along with the predicted S-R line and replacement lines for F=100% msp=0.00 and F40%msp = 0.17.

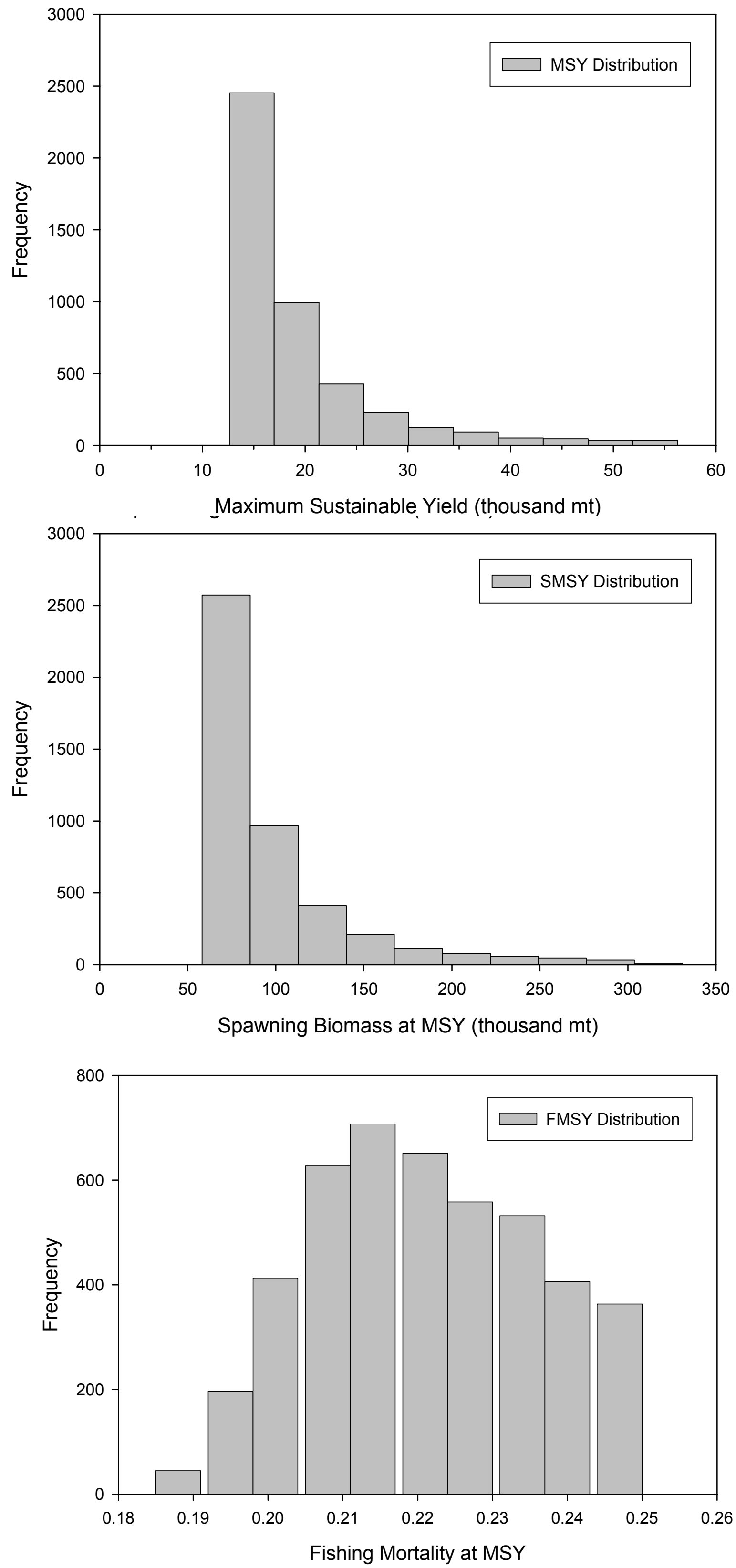


Figure 3.1.8. Gulf of Maine cod 11+ posterior distribution of MSY, BMSY and FMSY for most likely model fit.

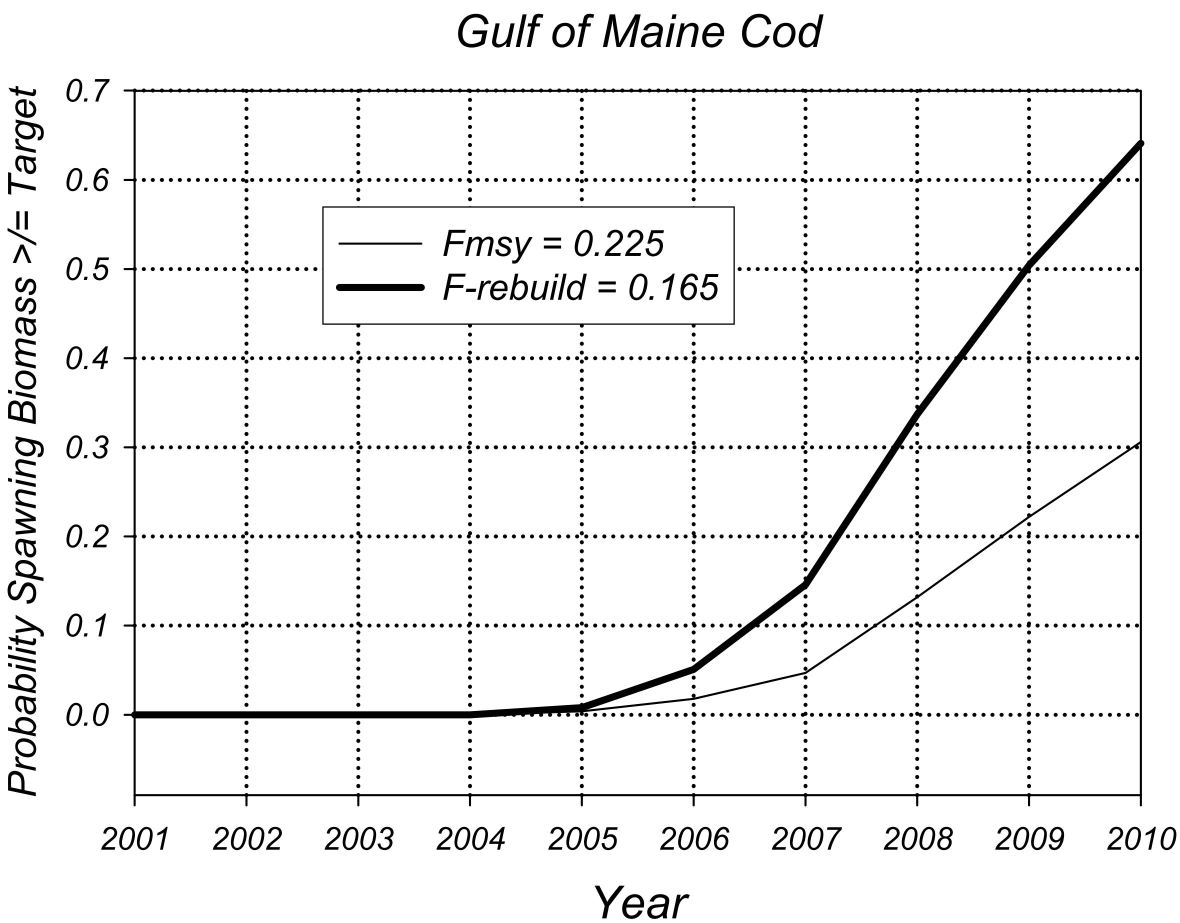


Figure 3.1.9. Probability that Gulf of Maine cod spawning biomass will exceed Bmsy (82,800 mt) annually under two fishing mortality scenarios: Fmsy and F required to rebuild the stock to Bmsy by 2009.

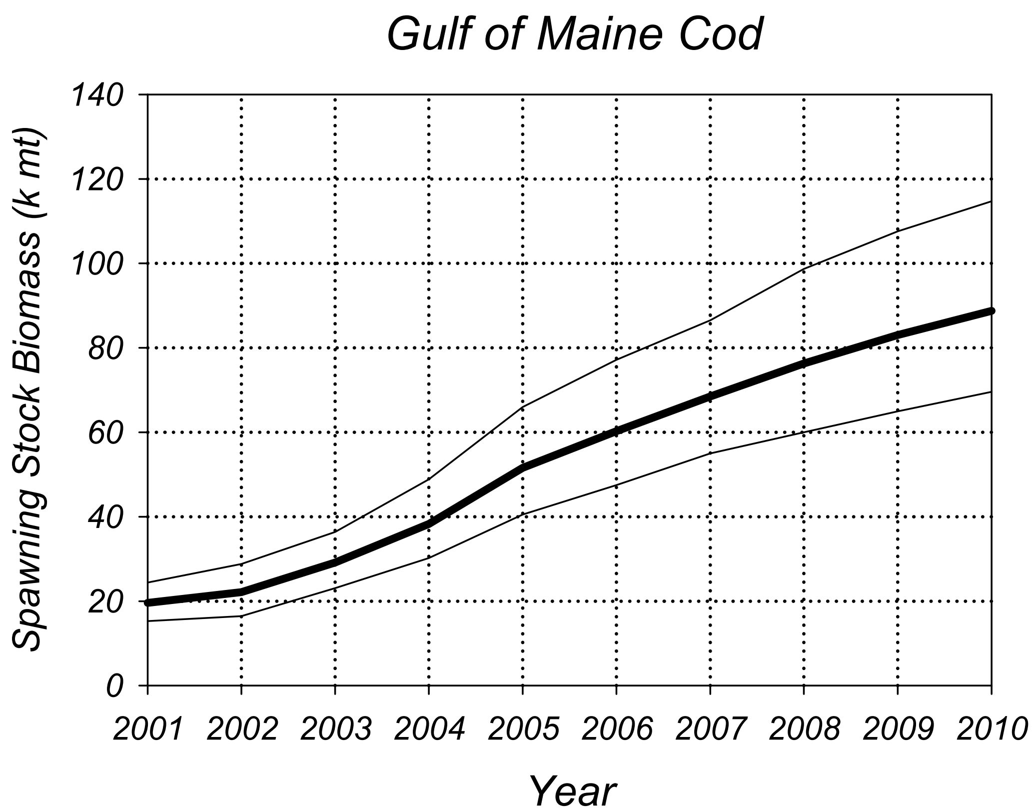


Figure 3.1.10. Median and 80% confidence interval of predicted spawning biomass for Gulf of Maine cod under F-rebuild fishing mortality rates.

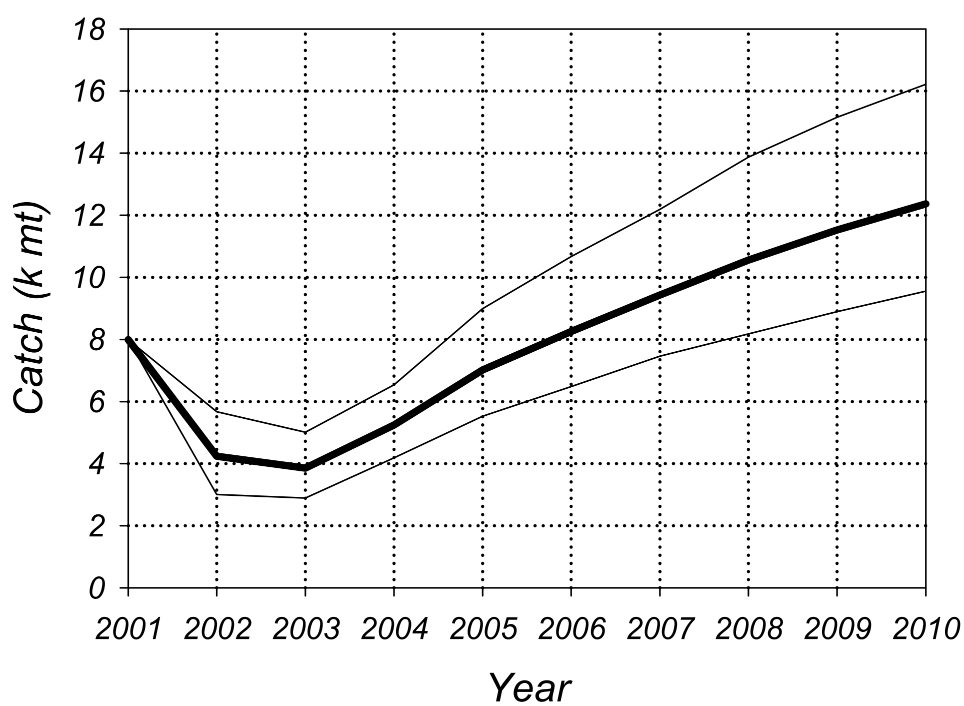


Figure 3.1.11. Median and 80% confidence interval of predicted catch for Gulf of Maine cod under F-rebuild fishing mortality rates.